TECHNICAL NOTE

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NEUTRONS IN SPACE

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SUMMARY

The various neutron sources in the solar system are discussed. Because of the neutrons' half-life, very few neutrons come into the solar system from outside. Cosmic rays interacting with the atmosphere or surface of the planets are the major neutron source near the planets. Studies of the neutron energy spectrum can give some information about the chemical composition of the planets.

The sun is a source of neutrons from several processes. Thermonuclear burn in the corona and leakage from the burning cone do not seem to be important sources, but a significant number of neutrons may result from high energy protons accelerated in flares on the sun.

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INTRODUCTION

First, a review of the production process used to explain neutrons in the earth's atmosphere will be given. These neutrons must be produced close by. Since the lifetime of the neutron is only about 10 minutes, neutrons cannot be made outside the solar system and still be observed at the earth. The process that generates neutrons in the atmosphere is the interaction of cosmic ray protons with oxygen and nitrogen nuclei. Neutrons in the energy range from about 0.1 to 5 Mev are made by evaporation, and higher energy neutrons are made by knock-on events. These neutrons slow down by collisions with nuclei, and an equilibrium spectrum is built up (Reference 1). The equilibrium neutron energy spectrum measured in the atmosphere is shown in Figure 1. By using neutron diffusion theory, the energy spectrum $\Phi(E)$ at all altitudes has been calculated (Reference 2); and the neutron leakage flux $J(E)$ is obtained by

$$J(E) = D \frac{\partial \Phi(E)}{\partial h} .$$

Summing over energy, we get the expected leakage neutron flux J in space, at geomagnetic latitude λ :

J (neutrons/cm² -sec)	λ (deg)
0.2	0
1.5	90

The energy spectrum of these leakage neutrons at different distances from the earth is shown in Figure 2.

MEASUREMENTS OF THE NEUTRON FLUX

There have been several experiments that measured the neutron flux in space near the earth. A moderated BF_3 counter was flown on an Atlas rocket capsule about two years ago and measured a
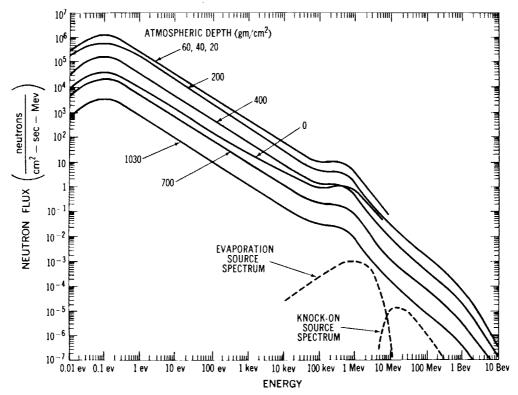
Figure 1—The equilibrium neutron flux versus energy at different depths in the atmosphere for geomagnetic latitude $\lambda = 44°$. The energy spectra for 200 to 1030 gm/cm² are experimental values; for depths less than 200 gm/cm² the spectra are calculated. The shapes of the two neutron source spectra are also shown.
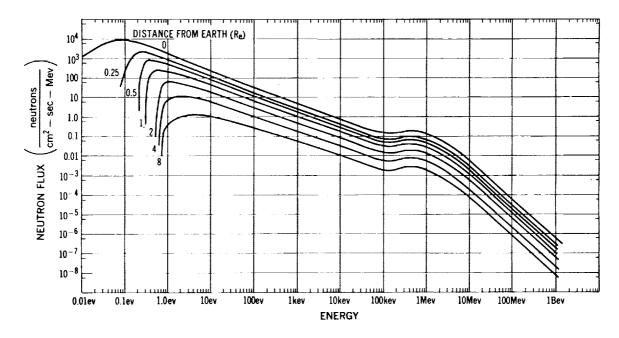

Figure 2—Neutron energy spectra in space at different distances from the earth above the geomagnetic equator (Dec. 1959). The curve for $R_e = 0$ is for the top of the atmosphere, which is roughly 100 km.

flux of 1.5 neutrons/cm^2-sec at about 40°λ and 200 km altitude (Reference 3)—about twice as large as the calculated leakage flux at this location. This difference is probably due to (p,n) events in the capsule. Protons striking the capsule will generate neutrons, some of which will be counted. These give an undesirable background, which needs to be eliminated.

A second BF$_3$ experiment was performed on an Atlas rocket that flew about three hours after the start of the November 15, 1960, flare. At this time sea level neutron monitors showed a large influx of solar particles. The neutron flux found on this flight was about three times larger than on the first flight and indicated that a new source of neutrons is present—very likely related to the solar proton influx. We will return to this point.

A third BF$_3$ Atlas experiment, which has not yet been completely analyzed, shows a neutron flux similar to the first flight. This third flight was made during a quiet time, so the flux measured on the first and third flights can be considered a quiet time neutron flux due to galactic cosmic rays.

A recent experiment by Pieper* on the TRAAC satellite, using moderated solid state detectors, showed somewhat smaller fluxes than those measured by the BF$_3$ detectors—smaller by a factor of about 2.

All these measurements are plagued by background troubles. Protons striking the neutron detector will generate neutrons that can be counted with a reasonable efficiency, and protons striking the vehicle carrying the detector will generate neutrons that also can be counted. These two backgrounds are considered separately because they can be eliminated by different experimental techniques. The background due to (p,n) events in the detector has been eliminated by using a moderated neutron detector where the moderator is a scintillator.

A system of this type recently was flown on two Discoverer satellites. An anticoincidence circuit rejects all neutrons made by protons in the detector. A chance coincidence circuit insures that the count rates are not so high that the anticoincidence circuit will not work correctly. The Discoverer satellite flies in a polar orbit at roughly 400 km altitude, so that a complete latitude and longitude survey of the neutron flux can be obtained in this way. A neutron flux of about 0.3 neutron/cm^2-sec was measured at the equator and about 3 neutrons/cm^2-sec at the pole. These values are consistent with the Atlas data and are about two times larger than the calculated leakage neutron flux. The problem here is that very likely the background of neutrons made in the vehicle, which are counted by the detector, has not been taken care of or eliminated. Currently two methods are being used to get at this background: calculating it approximately, and also measuring it indirectly. These methods should give a reasonable estimate of the background, but the proper way to deal with it is to eliminate it by placing the detector on an arm far enough away from the vehicle so that the background is negligible. This, coupled with the scintillator moderator, should eliminate all backgrounds. Such detectors will be flown in the future.

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*Private communication from G. Pieper.

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NEUTRONS FROM SOLAR PROTONS

Protons coming to the polar caps of the earth from the sun at the times of certain flares provide another source of neutrons (Reference 4). These solar protons will generate neutrons by collisions with O and N nuclei in the same way that galactic cosmic rays do; this can be a quite strong source of neutrons. A large solar proton event might bring 10^5 protons/cm^2-sec to the polar caps, which may make 10^4 neutrons/cm^2-sec or more leaking out of the polar atmosphere. If this proton event lasts for 10^4 seconds, it will produce about as many neutrons in this short time as galactic cosmic rays do in 1 year.

Two characteristics of these polar neutrons are different from those produced by galactic cosmic rays: They will be of lower energy because the solar protons are mostly of E < 100 Mev; and, also, they are restricted in their spatial distribution. They will be generated from roughly λ = 60° to 90°, so they cannot be observed at the equator at low altitude because the earth is in the way. At λ = 40° at 500 km, where the Atlas measurement was on November 15, 1960, only the edge of the production region can be seen. The enhanced flux observed by this experiment is quite certainly polar neutrons. But, if the experiment had been conducted at λ = 60° or more, the effect should have been much larger. It is important to try to determine the properties of these polar neutrons accurately because they may play a very important role in the formation of the outer radiation belt. They may be as much as one hundred times more important a source for the outer belt than are the neutrons produced by galactic cosmic rays (Reference 5). Time variations seen in the inner belt, L $\approx$ 2, may be due to particles trapped from the decay of polar neutrons.

NEUTRONS FROM THE MOON AND PLANETS

Neutrons will be generated by cosmic rays striking the surface of the moon (Reference 6). This source will be stronger than in the earth's atmosphere for three reasons: First, the moon has a very weak magnetic field, and thus low energy cosmic rays can reach it. Second, the neutron production takes place in a heavier material and, because the cross section for neutron production increases with atomic weight A, more neutrons will be made on the moon. Third, π-mesons made by high energy reactions can interact to make more neutrons on the moon. In the atmosphere of the earth the π-mesons all decay to μ-mesons before interacting, so that no neutrons are made by π-mesons on the earth. The combination of these effects increases the neutron flux by a factor of about 10.

An interesting possibility, related to the leakage neutrons, exists on the moon. The shape of the energy spectrum of the leakage neutrons depends quite sensitively on the amount of hydrogen present, as H is a very powerful neutron moderator. If H is present on the moon, the Mev neutrons are rapidly slowed down to thermal energies and a thermal peak is produced. By measuring the shape of the spectrum, a reasonable estimate of the hydrogen can be made. The presence or absence of H is quite important in understanding the origin and history of the moon.

Galactic cosmic rays make neutrons in the atmosphere of Venus also (Reference 7). Venus' atmosphere is known to be composed of CO_2 with very small amounts of H_2O and CO present. Nitrogen

may or may not be there; this is not known. The energy spectrum of the neutrons in the Venusian atmosphere will be changed if N is there. Neither C nor O are good neutron absorbers, but N is; so the population of thermal neutrons will be lessened by the presence of N. This might be one way of measuring the amount of N in the Venusian atmosphere.

NEUTRONS FROM THE SUN

The sun will be a source of neutrons from several processes. First, there will be the usual neutrons made by galactic cosmic ray protons. Since the sun has only about 10 percent helium, this neutron source will be considerably weaker for the sun than for the earth. The cosmic ray protons will not generate many neutrons from interacting with the hydrogen in the sun because the threshold for the process

$$p + p \longrightarrow \pi^+ + n + p$$

is for a proton energy of about 300 Mev. Even above this energy, the cross section for this reaction is small. Thus this cosmic ray neutron source is not important in our considerations.

Another source of neutrons on the sun is thermonuclear reactions in the corona. The corona has a temperature of about 10^6 °K, or the particle energies are about 100 ev. There is a ratio of about 5×10^{-5} of D/H atoms (Reference 8), and we will expect some reactions of the type

$$D + D \longrightarrow n + He^3 \ .$$

There is so little tritium that reactions involving it are probably not important. The cross section for the DD reaction is dominated by the coulomb barrier penetration term. The cross section times velocity, averaged over a Maxwellian velocity distribution (Reference 9), is given as

$$<\sigma v> \ = 2.6 \times 10^{-14} \ t^{-2/3} \ \exp \left[-18.76 \ t^{-1/3} \right]$$

$$= .4 \times 10^{-30} \ \text{cm}^3/\text{sec for a temperature of } 10^6 \text{°K.}$$

The reaction note R for this process is given by

$$R \ = \frac{n^2}{2} <\sigma v> \ \text{reactions/cm}^3\text{-sec,}$$

where n is the number density of D atoms. Assuming that $n = n_0 \left(R/R_\odot \right)^{-m}$, we can write the total production P of neutrons in the corona as

$$P \ = \int R \, dV \ = \int k \frac{n_0^2}{2} \left(\frac{R}{R_\odot} \right)^{-2m} <\sigma v> 4\pi R^2 \, dR \ \text{neutrons/sec} \ ,$$

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where k is the neutron yield per DD reaction. The value of k is about 1/2 because the probabilities of the two possible reactions,

$$D + D \longrightarrow n + He^3$$

and

$$D + D \longrightarrow p + H^3 \, ,$$

are essentially equal.

Evaluating $n_0 = 2 \times 10^8$ and $m = 7.5$ for the known electron densities in the corona (Reference 10), we then get for the neutron flux at the earth:

$$\Phi = \frac{P}{A} = \frac{k n_0^2 <\sigma v> 2\pi R_\odot^3}{4\pi R_e^2 (2m - 3)} = 5 \times 10^{-10} \text{ neutron/cm}^2\text{-sec} \, ,$$

where R_e is the earth-sun distance. This number is very small and cannot be measured. Reactions below the corona of the sun are not important because the temperature rapidly goes down to 10^4 °K and the reaction rate becomes vanishingly small.

When a big flare comes along, there may be an important number of thermonuclear neutrons in the region of the corona above the flare. The temperature of the corona sometimes increases to about 3×10^6 °K, according to soft x-ray data of Freidman (Reference 11). The D/H ratio can increase to 1/10, according to Goldberg (Reference 12), at the time of a flare—much larger than the quiet-time value of 5×10^{-5} used here from Severnyi (Reference 8). From these factors,

$$\left(\frac{.1}{3 \times 10^{-5}}\right)^2 \frac{(.3)^{-2/3} \exp\left[-18.76 (.3)^{-1/3}\right]}{(.1)^{-2/3} \exp\left[-18.76 (.1)^{-1/3}\right]} = 1.1 \times 10^{12} \, .$$

The flare may cover an area of 10^{-4} of the sun's distance, which will give an additional neutron flux at the earth of

$$\Phi = \left(5 \times 10^{-10}\right)\left(1.1 \times 10^{12}\right) \times 10^{-4} = 6 \times 10^{-2} \text{ neutron/cm}^2\text{-sec} \, .$$

If the density in a condensation above a flare went up by a factor of 100, the flux would be measurable; but this process does not seem normally to be a big neutron source. There is some evidence for thermonuclear reactions in flares on the sun in the work of Fireman (Reference 13), who analyzed the Discoverer 17 vehicle that flew during a flare and found excess tritium; but, for now, we will pass over this source.

Next we should consider the possibility that neutrons from inside the sun, made in the burning region, can get to the surface. Fowler (Reference 14) has given D/H = 10^{-17} for the burn region for

$T = 15 \times 10^7$ °K. Using the energy output of the sun of 6×10^{10} ergs/cm^2-sec, we have

$$\frac{\left(6 \times 10^{10}\right) \times 4\pi \left(1.2 \times 10^{11} \text{ cm}\right)^2}{28 \text{ Mev} \left(1.6 \times 10^{-6} \text{ erg/Mev}\right)} = 2.4 \times 10^{38} \text{ pp reactions/sec .}$$

Assuming the same cross section for pp as for DD, we get about 10^4 neutrons/sec formed. Taking the decay mean life as the lifetime of a neutron, we can obtain an upper limit on the total neutron population at the sum of 10^7 neutrons.

Now, we must see what fraction of these can leak out through about $.5 \times 10^{11}$ cm of $\bar{\rho}=1$ material. The important numbers for slowing down and diffusion for H_2O are:

	Length (cm)	Time (sec)
Slowing Down	6	10^{-5}
Diffusion	2.9	2×10^{-4}

These numbers are probably rather similar to the sun, which is mostly hydrogen and $\bar{\rho}=1$. From these numbers we see that slowing down to thermal energy occurs very rapidly and then diffusion proceeds. This represents $.5 \times 10^{11} / 2.9 = 1.7 \times 10^{10}$ diffusion lengths, which means $\left(1.7 \times 10^{10}\right)^2 = 3 \times 10^{20}$ random walk steps, or a time of $\left(3 \times 10^{20}\right) \times \left(2 \times 10^{-4}\right)$ sec $= 6 \times 10^{16}$ sec. With a factor e of the neutrons lost after each diffusion length, due to absorption, then the fraction of neutrons that leak out of the sun is $e^{-3 \times 10^{20}} \approx 10^{-87}$. This neutron source is rather small!

There is, however, another neutron source on the sun that may not be small. At the time of some large flares, large fluxes of protons arrive at the earth. These fluxes may exceed 10^5 protons/cm^2-sec for proton energies of $E_p > 10$ Mev, and they may last for $\approx 10^4$ sec. This represents at the sun a total energy t of about

$$t = 10^5 \frac{\text{protons}}{\text{cm}^2\text{-sec}} \times 10^4 \text{ sec} \times \left[1/4\pi \times 4\pi \left(1.5 \times 10^{13} \text{ cm}\right)^2\right] 10^{-14} \text{ erg/proton ,}$$

where we have taken 1 steradian as the size of the proton beam. This gives

$$t = 5 \times 10^{30} \text{ ergs .}$$

This is the order of 1 percent of the observable energy released in a large flare. The mechanics of a flare is not known; but it is not at all impossible that an equivalent-or larger-number of protons go down into the sun and, by interacting, make a large number of neutrons. It is thought that some solar radio bursts may be due to energetic electrons that go down into the sun and make bremsstrahlung. If we guess that an equal number of protons go down and go up, we then have $\approx 5 \times 10^{30}$ protons/sec going downward; and, if they each make on the average 0.01 neutron by interacting with solar material going out in 4π steradians, we will get

$$\frac{\left(5 \times 10^{30}\right)\left(.01\right)}{4\pi \left(1.5 \times 10^3\right)^2} = 26 \text{ neutrons/cm}^2\text{-sec at the earth.}$$

This number will be reduced some by the decay of neutrons on their way to the earth. This is a large flux and should be easily observable at the top of the earth's atmosphere. Because these neutrons will be of low energy E < 100 Mev, they will not be seen at sea level but only aloft.

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